

Analysis of the Radiation Hardness and Charge Collection Efficiency of Thinned Silicon Diodes

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I. SUMMARY

In the past decade, R&D in silicon radiation detectors has been mainly focused on radiation hardness issues as required by the application of these devices in high luminosity colliders. Radiation damage induces several detrimental effects on high resistivity silicon detectors [1]: among them, the increase of the full depletion voltage after substrate type inversion is of particular concern. Very thin detectors (50-100 μm) are one possible strategy to face this problem [2]. The direct advantage of such approach is the reduced depletion voltage even after high radiation fluences. Moreover, the starting resistivity of a thin sensor can be much lower than that of a standard 300 μm thick detectors, still preserving a low depletion voltage and, as a consequence, the type inversion can be delayed. Furthermore, an improvement of the tracking precision and momentum resolution is expected.

Due to severe handling problems with standard equipment in fabrication lines, mechanical lapping cannot be used to thin the wafers down to 50-100 μm thickness. Thus, the most convenient approach is a local thinning, which can be performed adopting the wet anisotropic silicon etchant TMAH (Tetra-Methyl Ammonium Hydroxide), that, among the other techniques available, has gained considerable interest because of its CMOS compatibility. Furthermore, the TMAH shows a very good etching uniformity and a relatively high selectivity for silicon with respect to oxides and nitrides at some fixed TMAH wt% concentrations [3].

We have already reported on the development of a fabrication technology for the realization of PIN diodes on membranes obtained by locally thinning the silicon substrate by means of TMAH etching from the wafer backside [4]. The fabrication process of a detector on a silicon membrane is based on a pre-existent technology developed at ITC-irst for silicon detectors,

adding the etching step of the wafer backside during device processing. Two membrane thicknesses (50 and 100 μm) have been obtained by etching for different times silicon wafers 300 μm thick, $\langle 100 \rangle$ oriented, phosphorus-doped, with a nominal resistivity of 6 $\text{k}\Omega\cdot\text{cm}$. The schematic cross-section of a thinned device obtained with this approach is shown in Fig. 1, whereas Fig. 2 shows a Scanning Electron Microscope (SEM) photograph of the structure.

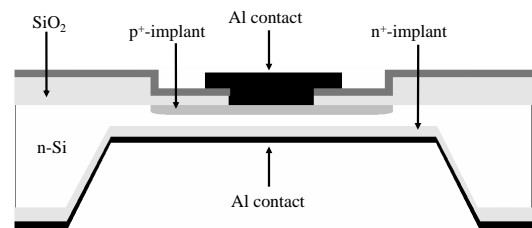


Fig. 1. Schematic cross-section of a PIN diode on thinned membrane.

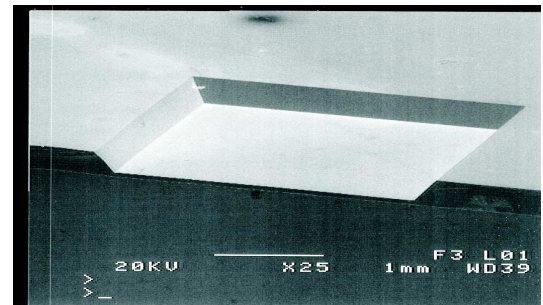


Fig. 2. SEM photograph of the backside of a 50 μm thick TMAH thinned PIN diode.

This study was performed in the framework of the CERN RD50 Collaboration.

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No appreciable differences have been observed between the electrical characteristics of devices made from thinned and non-thinned (300 μm) reference wafers [4]. This confirms that TMAH can be reliably used as an etching technique without degrading the detector performance. A summary of the main electrical parameters measured on test diodes of different thicknesses is given in Table I.

In order to evaluate and compare the radiation hardness of thinned devices with respect to 300 μm thick detectors, samples have been irradiated at the SIRAD Irradiation Facility of the INFN National Laboratory of Legnaro (Padova, Italy) [5] with

TABLE I

SUMMARY OF THE MAIN ELECTRICAL PARAMETERS OF PIN DIODES MADE FROM SUBSTRATES OF DIFFERENT THICKNESS.

Thickness (μm)	Full depletion voltage (V)	Leakage current density (nA/cm^2)
300	22 ± 2	533 ± 33
100	2.2 ± 0.4	303 ± 40
50	1.2 ± 0.2	368 ± 35

58 MeV Li ions at four different fluences up to $1.83 \times 10^{13} \text{ Li}/\text{cm}^2$. The hardness factor for 58 MeV Li ions in 300 μm thick silicon diodes has been determined by measuring the damage constant and found to be 45.08 ± 0.04 [6], i.e., about 25 times higher than the corresponding value (1.8) for 27 MeV protons, suggesting that irradiation by 58 MeV Li ions can be used for accelerating the detector testing in High Energy Physics applications, with the advantage that high bulk damage levels in the detector active layer can be reached at moderate ion fluences, thus decreasing the irradiation time, if the fluxes of Li ions and other particles used for irradiation tests are similar.

Fig. 3 shows the depletion voltage (V_{dep}) as a function of the Li fluence, as obtained by 10 kHz C-V measurements, for diodes of different thickness. As can be seen, devices made from thinned substrates exhibit a very low depletion voltage even after the maximum fluence. In particular, V_{dep} does not exceed 6 V for the 50 μm thick detectors, confirming the expected higher radiation hardness with respect to 300 μm thick sensors, for which $V_{dep} = 230 \text{ V}$ already at $1 \times 10^{13} \text{ Li}/\text{cm}^2$.

As expected, the leakage current volume density (J_D) linearly increases with the Li fluence (see Fig. 4), even if the damage constant (α), i.e., the slope of the linear fit of the J_D data, decreases by increasing the detector thickness. This effect, already discussed in [7], is due to the fact that, although the range of the 58 MeV Li ions is 400 μm , the damage produced in 300 μm thick diodes increases with increasing the depth in the Si bulk. Nevertheless, we remark that the α values shown in Fig. 4 are in agreement with the results reported in [6],[7], suggesting that the considerations in [6],[7] for the Li ion induced damage in thick and thin silicon detectors are independent on the the diode manufacturer, at least for what concerns the α parameter.

Charge collection efficiency (CCE) tests with a ^{90}Sr β particle source (0.1 mCu) are under way at INFN-Florence on both non-irradiated and irradiated samples. Results from measurements performed on non-irradiated diodes show that the CCE correctly scales with diode thickness, in agreement to the model given in [8].

In order to deeply investigate: 1) the radiation hardness of the thinned diodes with respect to standard 300 μm thick devices; 2) the radiation damage induced by Li ions with respect to hadrons, further irradiation are now under way at the CERN-PS accelerator with 24-GeV protons up to $1 \times 10^{16} \text{ protons}/\text{cm}^2$ and at the SIRAD irradiation facility with Li ions at higher fluences. This will allow to present at the Conference the full

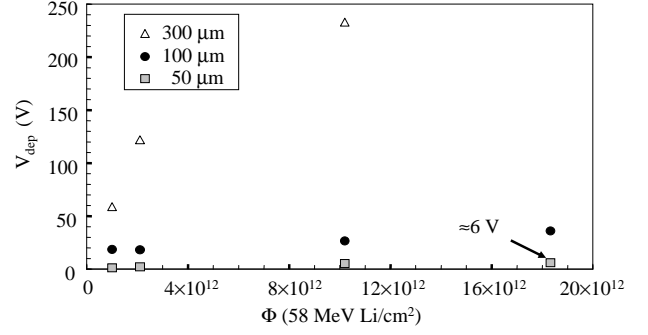


Fig. 3. Depletion voltage (V_{dep}) as a function of the Li ion fluence (Φ) for PIN diodes of different thickness.

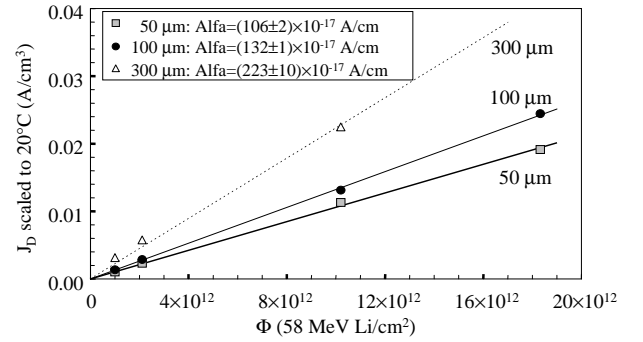


Fig. 4. Leakage current volume density (J_D) as a function of the Li ion fluence (Φ) for PIN diodes of different thickness. The values of the damage constant α , i.e. the slope of linear fit for the J_D data, are reported in the inset.

panorama of the results on CCE, depletion voltage variation and leakage current increase for thinned and standard 300 μm thick devices before and after irradiation with both Li ions and protons.

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